

# The relative importance of soil crust and slope angle in runoff and soil loss: a case study in the hilly areas of the Loess Plateau, North China

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**Abstract** Soil crust and slope angle are of important factors affecting runoff production and sediment yield. In the hilly areas of the Loess Plateau, North China, slope lands are distributed extensively and subjected to soil crusting; therefore, the research on the responses of runoff and soil loss to soil crust and slope angle is essential to soil and water conservation. In the study, five pairs of 1 m × 5 m plots with slope angles of 5°, 10°, 15°, 20° and 25° respectively, were established in Wangjiagou watershed, which was located at the Loess Plateau, China. Based on the two simulated rainfall events, uncrusted surface prior to the first simulated rainfall event, and crusted surface prior to the second rainfall event were distinguished. The runoff production and soil loss were measured at intervals of 5 min during the simulated events. It indicated that both soil crust and slope angle played an important role in runoff production and soil loss. With the reference slope angle of 5°, the relative importance of soil crust and slope angle in runoff production was calculated. It showed that soil crust effect on the total runoff volume decreased from 100 to ~40%, while slope angle effect

increased from 0 to ~60% with increasing slope angle because soil crust less developed on the steeper slopes. Furthermore, soil crust effect was associated with rainfall duration. At the same slope angle, the relative importance of soil crust decreased with rainfall duration because new crust was formed on the uncrusted surface. The critical slope of erosion was also discussed. Soil loss increased with slope angle when the slope angle was less than 20°. Generally speaking, soil crust effect decreased with slope angle and/or rainfall duration.

**Keywords** Loess soil · Simulated rainfall · Soil and water conservation · Soil erosion

## Introduction

One of the most important responses of soil surface to heavy rain is the consolidation of surface particles to form soil crust (Farres 1978), which are restrictive surface layers reducing soil infiltration rates and increasing soil strength formed by the mechanical action of raindrop impact and the physicochemical response of aggregates to slaking and dispersion (Arshad and Mermut 1988). Soil surface crust formation, a common phenomenon occurring in most cultivated soils in many regions of the world has major implications for soil erosion because its effects on soil hydrological properties and soil erodibility. Soil crust increases runoff and may promote erosion

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due to its decreased permeability associated with greater bulk density, finer pores and lower infiltration rate compared with the underlying soil (McIntyre 1958a, b; Chen et al. 1980; Lado and Ben-Hur 2004; Fox and Le Bissonnais 1998; Le Bissonnais and Singer 1993). However, other researchers considered that soil crust increases soil strength and may reduce detachment and erosion (Moore and Singer 1990; Levy et al. 1994).

As an important topographic factor, slope angle has been the focus of research in soil and water loss. In many empirical equations slope angle has been considered as an important parameter in predicting soil losses (Valmis et al. 2005). Soil erosion was predicted as a power function of slope gradient in the early version of the USLE, and the relationship described as linear or less than linear has been taken into account in the Revised USLE (McCool et al. 1987; Fox and Bryan 1999). There exist contradictory results regarding the influence of slope angle on infiltration: infiltration rates increase, decrease, or remain unchanged with slope angle increases. The reason is not entirely clear, but it may be due to different sensitivity of soil crust or seal formation (Poesen 1984; Fox et al. 1997). Infiltration, runoff production and soil loss are three interdependent processes, therefore, slope angle plays an important role in runoff and soil loss through its effect on the hydraulic shear stress and the average velocity, the product of which determines the stream power and thus the overland flow erosivity (Nearing et al. 1991; Chen 1983). In general, an increased slope angle gives a higher potential for runoff (Hudson 1995).

However, field observations revealed that the runoff increases in some cases, while it decreases or is not significantly different in others as slope gradient increases.

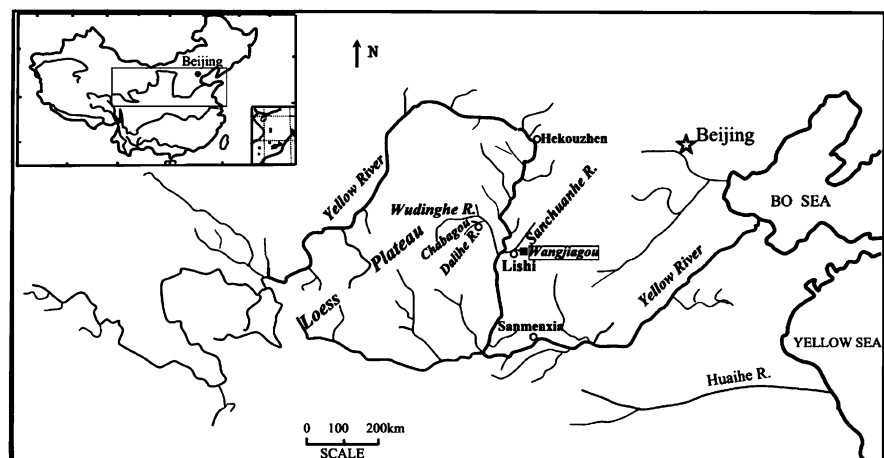
Many factors influence infiltration rate, runoff production and soil loss. These include rainfall characteristics, topographic features, soil surface conditions, vegetation coverage, but the list is not exhaustive. Once exposed to rainstorms, bared loess soils especially those in cultivated fields are prone to form soil crust (Cai et al. 1986; Luk et al. 1989) and, runoff production and soil loss may be changed. Despite numerous studies, soil crust effect at different slope angle remains unclear. Hence, the aims of the study are mainly to investigate soil crust effect and slope angle effect on runoff production and soil loss, and to reveal the relative importance of them.

## Materials and methods

### Experimental set-up

The 9.1 km<sup>2</sup> Wangjiagou watershed (Fig. 1) was selected for field experiments because its natural condition is strongly representative in the hilly loess region. It is located at the Loess Plateau, China (111°8'E, 37°32'N), about 4 km north of Lishi County, Shanxi Province. The region is covered by a thick loess mantle, and falls in a temperate semi-arid zone. The average annual precipitation is about 505.7 mm, approximately 80.6% of which falls from May to September and corresponds to short duration,

**Fig. 1** Location of Wangjiagou watershed in the Loess Plateau, China (modified from Zheng et al. 2008)



high intensity storms (Cai 2001). The annual sediment yield is often attributed to one or several single heavy storms (Cai et al. 1998). At the Wangjiagou watershed, the topography undulates greatly, with an average slope angle of 30°. Slope lands with angles of <3°, 3–7°, 7–15°, 15–25°, 25–35° and >35° account for 5.14, 5.53, 19.54, 28.77, 28.01 and 13.01% of the whole watershed area, respectively (Fan et al. 2007). In addition, the loess soils, especially those in cultivated fields, are highly subject to surface crusting and sealing (Cai et al. 1986; Luk et al. 1989).

Five 2 m × 5 m (horizontal area) plots were performed on the cultivated slope lands. Each plot had one of five slope angles (5°, 10°, 15°, 20° and 25°) and was divided into two subplots: A and B representing two replications. In the bottom of each subplot, the Gerlach-type flume was used to collect runoff and sediment yield. The soil type was sandy loam. A few of the soil properties are presented in Table 1.

#### Rainfall simulations

Simulated rainfalls were generated by the rainfall simulator developed by Luk et al. (1986). It consists of stand-alone sprinkling units with a SPRACO cone jet nozzle that spray downwards. With a fall height of 4.57 m and water pressure of 67 kPa, drop sizes range from 0.35 to 6.35 mm, with a median of 2.40 mm. The total kinetic energy of simulated rainfall is 0.57 J m<sup>-2</sup> s<sup>-1</sup>, which represents approximately 90% of the kinetic energy of natural rainfall at a similar intensity.

The experiment contained two simulated rainfall events for five pairs of plots. Considering the peculiar rainfall characteristics of the high intensity and short duration in the study area, the two simulated rainfall

events lasted for 30 min at a high intensity of 1.2 mm min<sup>-1</sup>. During simulated rainfalls, rainfall intensity was monitored using four rain gages located at the plot edges, and runoff generation and sediment yield were collected at the bottom of each subplot with 5 min intervals from the moment that rainfall falling. Thereafter, runoff samples were oven-dried at 105°C for several hours to get soil loss values.

#### Soil surface treatment

To determine the effect of soil crust, all subplots underwent two runs of simulated rainfall. Prior to the first simulated rainfall event, in order to ensure that all plots have the same “initial conditions”, soil surface was cultivated till the depth of 12–15 cm and it represented the uncrusted surface. The measured water contents at the plots were about 13%. In short, soil surfaces were loose and very prone to form soil crust when exposed heavy rainfalls. After the first rainfall event, soil crust developed on soil surface and kept undisturbed. It represented the crusted surface. Air-dried for several days till the water contents got to about 13%, the second run of simulated rainfall fell. Thus, there were two soil surfaces, uncrusted surface prior to the first rainfall event and crusted surface prior to the second rainfall event.

#### Determination of soil crust effect and slope angle effect

To assess the relative importance of soil crust effect and slope angle effect, an assumption was put forward. An ideal level did not exist in the natural condition. Therefore, considering the smallest slope angle of 5° as the reference slope was an alternative method in the experiment.

**Table 1** Some chemical and physical properties of the five plots studied

Plots	Slope angle (°)	Soil texture <sup>a</sup>	Clay (%)	Silt (%)	Sand (%)	Organic matter (g kg <sup>-1</sup> )	CaCO <sub>3</sub> (%)
1	5	Sandy loam	13.82	27.05	59.13	6.9	10.71
2	10	Sandy loam	14.28	28.23	57.49	6.1	11.97
3	15	Sandy loam	13.49	27.91	58.60	5.8	13.18
4	20	Sandy loam	13.70	28.98	57.32	6.5	13.88
5	25	Sandy loam	13.53	27.30	59.17	5.4	12.70

<sup>a</sup> Classification of the International Society of Soil Science

The total runoff increment ( $\Delta R$ ) explains the differences of runoff production between crusted surface at slope angle of  $\alpha$  and uncrusted surface at the reference slope angle of  $5^\circ$ . It is calculated according to the following equation:

$$\Delta R = R_c(\alpha) - R_u(5) \quad (1)$$

where  $\Delta R$  is the total runoff increment;  $R_c(\alpha)$  is the runoff production under the crusted surface at the slope angle of  $\alpha$ ;  $R_u(5)$  is the runoff production under the uncrusted surface at the reference slope angle of  $5^\circ$ ;  $\alpha$  represents one of the five slope angles ( $5^\circ$ ,  $10^\circ$ ,  $15^\circ$ ,  $20^\circ$  and  $25^\circ$ ).

The runoff increment ( $\Delta R_x$ ) explains the differences of runoff production caused by slope angle. It is calculated according to the following equation:

$$\Delta R_x = R_u(\alpha) - R_u(5) \quad (2)$$

where  $\Delta R_x$  is the runoff increment;  $R_u(\alpha)$  is the runoff production on the uncrusted surface at the slope angle of  $\alpha$ .

The runoff increment ( $\Delta R_c$ ) explains the differences of runoff production due to soil crust. It is calculated according to the following equation:

$$\Delta R_c = R_c(\alpha) - R_u(\alpha) \quad (3)$$

where  $\Delta R_c$  is the runoff increment.

According to Eqs. 1–3, the relative contribution of soil crust ( $C_c$ ) and slope angle ( $C_x$ ) on runoff production can be calculated as follows:

$$C_x = \Delta R_x / \Delta R \quad (4)$$

$$C_c = \Delta R_c / \Delta R \quad (5)$$

where  $C_x$  represents the slope angle effect, and  $C_c$  represents the soil crust effect.

## Results and discussion

### Runoff initiation

Two runoff production patterns can be classified: (i) runoff results from excess rain, namely, runoff occurs when the rainfall intensity exceeds the soil infiltration capacity, while no surface runoff occurs if rainfall intensity is less than soil infiltration capacity; and (ii) runoff results from saturated soil, in other words, runoff occurs only when soil is saturated, while the

soil matric potential is negative and water is held in the capillaries due to the matric suction when the soil is unsaturated.

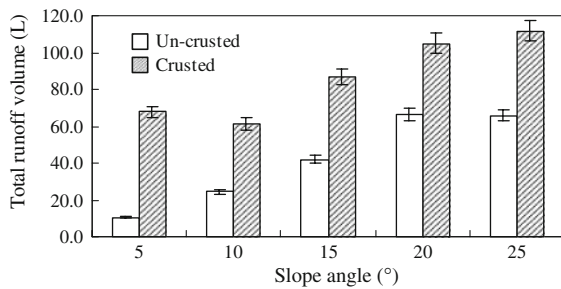
In the study area, the loess is too thick for the entire mass to become saturated in heavy storms, and runoff occurs only when rainfall intensity is greater than the infiltration capacity of the soil (Zheng et al. 2008). Thus, whether runoff occurs or not depends on greatly the relativity between rainfall intensity and soil infiltration capacity. Under the simulated rainfall events with the constant rainfall intensity, the time of runoff initiation on the different surface characteristics of the same soil provide the information of soil infiltration rate. Although direct measurements of soil infiltration rate could not be taken during rainfalls, soil crust effect on infiltration rate can be inferred from the runoff data.

Runoff was recorded on all plots in the experiments. However, the time of runoff generation was advanced on the crusted surfaces compared to the uncrusted surfaces. Runoff initiated on the crusted and uncrusted surface when the rainfall lasted for 10 min and 15 min, respectively. This suggested that infiltration rate could be substantially reduced by soil crust formation, so that the risk of runoff production is greatly enhanced. In the Yangdaogou catchment, which is located in the Wangjiagou watershed, Zhu et al. (1997) concluded that soil crust was one of the most important factors affecting soil infiltrabilities, and soil crust formation reduced the infiltrability of loess soils, from 0.6–0.7 to 0.2–0.3 mm min<sup>-1</sup> or so.

### Runoff production

Total runoff volumes on crusted and uncrusted soil surfaces at different slope angles are given in Fig. 2. There are considerable variations in the runoff volume, both within different slope angles on the same soil surface, as well as between different soil surfaces at the same slope angle. Though the susceptibilities of soil crust formation at different slope angles were not investigated directly in the study, the effects of soil crust could be reflected by comparing crusted and uncrusted soil surface treatments.

At the same slope angle, the larger value was always observed on the crusted surface, and the lower value was associated with the uncrusted surface (Fig. 2). This reinforced the effect of soil crust on



**Fig. 2** Total runoff volumes on crusted and uncrusted surfaces at five slope angles (Error bars represent  $\pm 5\%$  of errors)

reducing infiltration rate and enhancing runoff volume. In the case of uncrusted surface, soil surface was rough and loose, and the capacity of water storage and permeability was high, therefore, the runoff amount was low, but the reverse was true for the case of crusted surface. This interpretation was supported by Gomez and Nearing (2005), who found that runoff was less on the rough surface for the first rainfall application but greater on the final three, probably due to the formation of a depositional seal. Neave and Rayburg (2007) also considered that the initial crust development was an important contributor to the runoff.

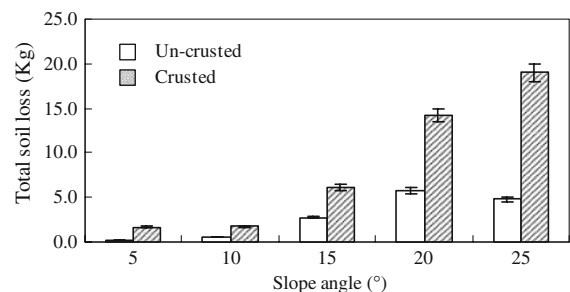
In most cases, the total runoff volume increased with slope angle, except that no apparent differences between slope angles of  $20^\circ$  and  $25^\circ$  on crusted and uncrusted surfaces (Fig. 2). This suggested that accumulative infiltration decreased considerably with increasing slope angle especially when the slope was less than  $20^\circ$ . Chen and Cai (1990) found that the when slope angle was less than  $18^\circ$ , infiltration decreased greatly with slope, while slope angle was steeper than  $18^\circ$ , infiltration was less influenced by slope angle. Jin (1996) investigated that the turning point of slope angle was  $15^\circ$ . However, Fox and Bryan (1999) observed that infiltration rate decreased from about  $9.8$  to  $7.5 \text{ mm h}^{-1}$  with increasing slope gradient (2.5, 11.5, 20.5, 30 and 40%) without the turning point since the influences of slope angle on infiltration rate occurred dominantly through its influence on overland flow depth (Fox et al. 1997). Luk et al. (1993) considered that changes of infiltration rate with slope angle were influenced by rainfall time. During short storms, infiltration rate increased with increasing slope angle, due to the soil crust developed more rapidly on the lower slope angles.

Once the seal was well developed at all slope angles, infiltration rate decreased with increasing slope angle, because of the dominant influence of slope angle on overland flow depth and surface storage. Soil crust effect related to rainfall duration was discussed in detail later.

### Soil loss

The total soil loss on crusted and uncrusted surfaces is presented in Fig. 3. The differences between soil loss amounts existed both within the same soil surface at different slope angles, as well as between different soil surfaces at the same slope angle.

In all cases, soil loss was lower on uncrusted surface not only due to the lower runoff production but also the greater level of hydraulic resistance originated from its roughness that dissipated the energy of flow, making a fraction of the total flow energy unavailable for transport of sediment (Gomez and Nearing 2005). The total soil loss on the crusted surface with the reduced soil erodibility did not show the decreased trend comparing with the uncrusted surface due to the erosive forces of large amount of runoff. This illustrated that the shear stresses of flow were increased due to seal formation and implied that erosion rates on crusted surfaces were controlled by runoff capacity (Neave and Rayburg 2007). Other researchers (e.g. Fox and Bissonnais 1998) also reported a positive relation between soil crust development and erosion rate. However, different results were observed that the erosion rate was higher on the uncrusted plots than that on the crusted plots. This was because the loose debris on the uncrusted surface



**Fig. 3** Total soil loss on crusted and uncrusted surfaces at five slope angles (Error bars represent  $\pm 5\%$  of errors)

could easily be removed or flushed away at the early stage of runoff generation (Zhu 2002). In field trials, Fox et al. (2004) also concluded that breaking the surface crust increased erosion considerably since tillage brought to the surface an abundant supply of loose sediments.

With the increase of slope gradient, the stability of soil on slope surface decreased, and thus the soil loss increased under the same rainfall event. However, many scientists found that there existed a critical slope no matter what from the viewpoint of energy theory or from the result of simulated experiment (Wu 1997; Chen et al. 1988; Hu and Jin 1999). The sediment yield from over-land flow erosion increased with increasing slope if the slope was smaller than a critical value, and then reduced with increasing of the slope if the slope was larger than the critical slope. Hu and Jin (1999) reviewed the critical slope of erosion, and concluded that the critical slope gradient depended on the flow discharge, runoff depth and grain size distributions. It was not a fixed value, but a range of values, for example, 22–33° (Wu 1997), 25–28° (Chen et al. 1988), 24–29° (Jin 1996). In the experiment, runoff production at the slope angle of 20° was nearly the same as that at 25° on crusted and uncrusted surfaces, and soil loss on uncrusted surface at the slope angle of 25° was lower than that at 20°. However, on crusted surface, soil loss increased with slope gradient (Fig. 3), the critical slope had not been reached yet. This suggested that the critical slope of overland flow erosion could be in the range of 20–30° (Hu and Jin 1999).

The relative importance of soil crust and slope angle

Soil erosion ( $E$ ) is function of five variables, including climatic factor ( $C$ ), soil properties ( $S$ ), topography ( $T$ ), soil surface characteristics ( $SS$ ) and man-made behaviors ( $M$ ) (Renard and Foster 1983). During the experiment, climatic factor, that is, the rainfall characteristics can be considered as the constant value. Soil properties presented in Table 1 showed that no major differences in particle size distribution, organic matter,  $\text{CaCO}_3$  content were observed. The initial soil water contents were also almost similar. In addition, all soil surfaces were bared during the experiment, that is, the influences of vegetation cover/type did not exist. Despite disturbance occurred

on the soil surface prior to the first rainfall event, it resulted in the changes of soil surface characteristics (crusted and uncrusted surface). As an important topographic factor, five slope angles were considered. Therefore, the differences in the experiment corresponded to soil crust effect and slope angle effect.

The factorial analysis of variance showed that both slope angle and soil crust affected significantly ( $P < 0.01$ ) the total runoff (Table 2).

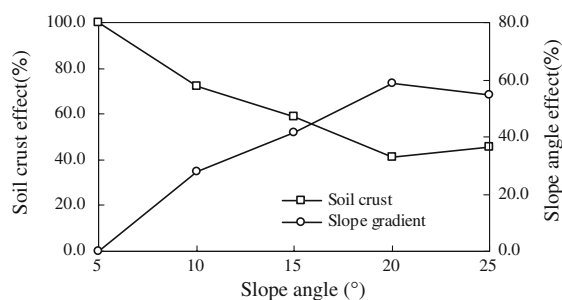
In order to determine the relative importance of soil crust effect and slope angle effect on runoff generation, the reference slope angle of 5° was assumed. According to the equations above-mentioned, the relative importance of soil crust and slope angle in total runoff was shown in Fig. 4. Soil crust effect decreased from 100 to ~40% with increasing slope angle, whereas, slope angle effect increased from 0 to ~60%. When slope angle was less than 15°, soil crust effect was dominant. However, when slope angle was steeper than 15°, slope angle effect was primary.

Soil crust effect decreased with slope angle. The possible explanation was that surface crust less developed on steeper slopes due to the lower normal

**Table 2** Factorial analysis of variance for selected parameters

Source of variation	Sum of squares	df	Mean square	$F^a$	$P$ -value	$F_{critical}$
Slope angle	4302.8	4	1075.7	33.5	2.5E-3	16.0
Surface treatment	5001.5	1	5001.5	155.8	2.4E-4	21.2
Error	128.4	4	32.1			
Total	9432.6	9				

<sup>a</sup>  $F$ -test, significant at the 0.01 level



**Fig. 4** The relative importance of soil crust and slope angle in total runoff at different slope angles



component of the drop impact force and the greater erosion rates (Poesen 1984). In addition, as slope steepness, more fine particles susceptible to be washed-in and clog pores below the soil surface were transported by overland flow, thus reducing the probability of pore clogging within the seal layer and its permeability (Assouline and Ben-Hur 2006).

Slope angle effect on soil erosion was realized by influencing soil infiltration. Infiltration decreased with increasing slope gradient, and so runoff yield increased (Jin 1996). As well as, flow velocity increased with increasing slope angle, the detention time was shortened greatly on steeper slopes and consequently, more runoff was recorded. Consequently, slope angle effect increased with slope angle.

#### Soil crust effect related to rainfall duration

The relative importance of slope angle and soil crust on runoff yield with rainfall duration at different slope angles were presented in Table 3. It should be noted runoff initiated on crusted and uncrusted surfaces at the rainfall duration of 10 min and 15 min, respectively. In addition, soil crust developed on different slope angles with different sensitivity. Consequently, the soil crust effect of 100% at the rainfall duration of 10 min was a relative value. The soil crust effect decreased but the relative slope angle effect increased as rainfall progressed. It indicated that soil crust effect was related to rainfall time.

Actually, soil crust can develop on the uncrusted surface during rainfall event. Thus, for storms with short duration, the antecedent crust is significant in generating runoff and soil loss. However, for storms

of longer duration, the effect is limited (Luk and Cai 1990). Zhu (2002) found the limited difference in runoff yield between the crusted and uncrusted plots, because the rapid development of new crusts at the beginning of a rain storm on the uncrusted plots would largely mask the difference between crusted and uncrusted plots, especially in the long-lasting and intensive storms.

#### Conclusions

The study confirmed that soil crust and slope angle had considerable effects on runoff production and soil loss. Soil crust formation advanced the time of runoff generation due to its effect on infiltration, and runoff volume and soil loss increased on crusted surface compared with that on the uncrusted surface. Runoff volume and soil loss increased with increasing slope angle till the critical slope angle of 20–30°. The relative importance which was calculated with the reference slope angle of 5° indicated that soil crust effect decreased with slope angle because soil crust less developed on the steeper slopes. In addition, soil crust effect was related to rainfall duration, and it decreased with rainfall time since new crust developed on the uncrusted surface.

Though runoff production and soil loss can be reduced by breaking soil crust, its effectiveness is limited due to the new crust formation during the subsequent rainfall events or, negative resulted from the loose materials (Zhu 2002). In addition, breaking by hoeing or other human behavior is passive and labor intensive endeavor. Raindrop impacting is the dominant driver to form soil crust on bare plots and

**Table 3** The relative importance of slope angle and soil crust on runoff production with rainfall duration at different slope angles<sup>a</sup> (%)

Rainfall duration (min)	10°		15°		20°		25°	
	Slope angle	Soil crust	Slope angle	Soil crust	Slope angle	Soil crust	Slope angle	Soil crust
10	0	100	0	100	0	100	0	100
15	13.85	86.15	0.17	99.83	37.69	62.31	20.15	79.85
20	26.57	73.43	12.18	87.82	44.01	55.99	34.19	65.81
25	32.74	67.26	28.92	71.08	53.50	46.50	46.05	53.95
30	27.87	72.13	41.29	58.71	58.85	41.15	54.68	45.32

<sup>a</sup> 5° is the reference slope angle

crust strength is influenced by rainfall impacts (Neave and Rayburg 2007). Aggregate breakdown, including shearing by raindrops and slaking for initially dry soils are the dominant process of soil crust formation. Hence, two general and active strategies can be adopted: surface protection and/or aggregate stabilization (Fox et al. 2004).

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